

# NLO EW corrections to color-charged SUSY particle production at the LHC

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LoopFest IX, Stony Brook, NY, USA  
June 22th, 2010

# Outline

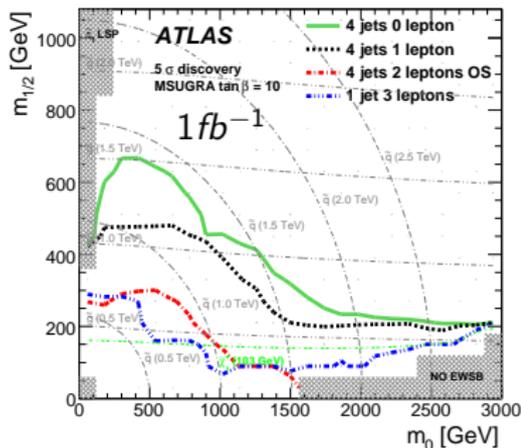
- 1 Introduction to **colored SUSY** particles @ LHC
  - Production processes
  - Status of higher order corrections.
- 2 **EW** contributions to **squark** and **gluino** production:
  - **EW tree-level** contributions.
  - **NLO EW** contributions of  $\mathcal{O}(\alpha_s^2\alpha)$ .
- 3 Numerical results
  - **Total cross-sections**
  - **Scale dependence** of EW contributions.
- 4 Conclusions

# Colored SUSY particles @ hadron colliders

- **Squarks** and **gluinos** are **strongly interacting** particles.  
→ large cross sections at pp colliders.

Production rate further enhanced due to:

- $\tilde{t}_1$ : often **lightest squark**  
(large top-Yukawa coupling).
- $\tilde{q}$ : **high multiplicity**  
(flavor, chirality).
- $\tilde{g}$ : **color-octet** representation.

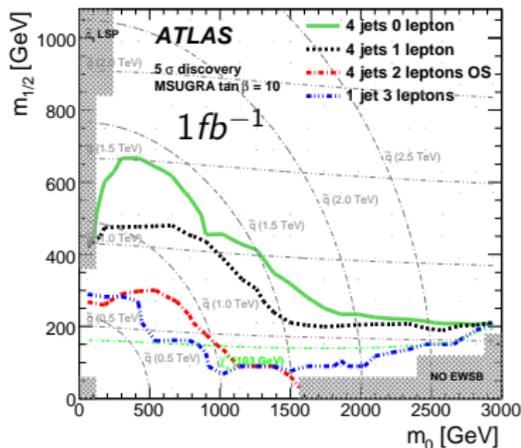


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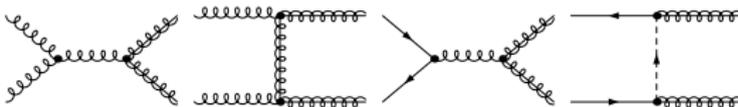
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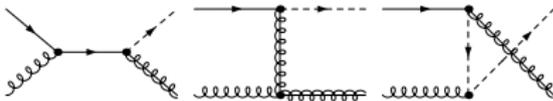
**Good prospects for discovering SUSY!**

# Overview: Production processes at LO

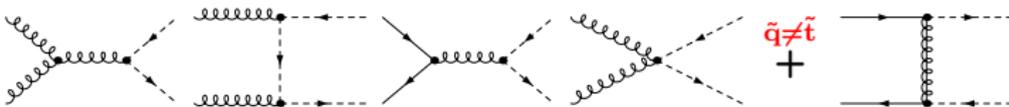
$\tilde{g}\tilde{g}$



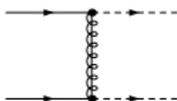
$\tilde{q}\tilde{g}$



$\tilde{q}_i\tilde{q}_i^*$   
 $\tilde{b}_i\tilde{b}_i^*$   
 $\tilde{t}_i\tilde{t}_i^*$



$\tilde{q}_i\tilde{q}_j$



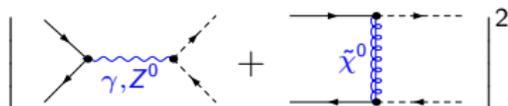
[Kane & Leveille '82, Harrison & Llewellyn Smith '83, Reya & Roy '85  
Dawson, Eichten, Quigg '85, Baer & Tata '85]

# Status of higher order corrections

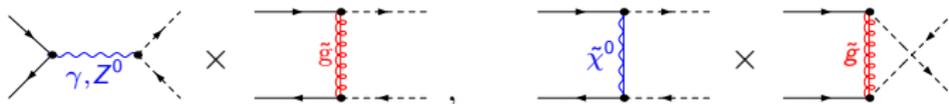
- $\mathcal{O}(\alpha_s^3)$ : NLO QCD corrections for all production processes known
  - [Beenakker, Höpker, Spira, Zerwas '95&'97],
  - [Beenakker, Krämer, Plehn, Spira, Zerwas '98]
  - PROSPINO
- Beyond NLO QCD:
  - Approximate **NNLO** corrections ( $\tilde{q}\tilde{q}^*$ )
    - [Langenfeld, Moch '09],
    - [Kulesza, Motyka '08'09],
    - [Beneke, Falgari, Schwinn '07'09],
    - [Beenakker, Brensing, Krämer, Kulesza, Laenen, Niessen '09]
  - **NLL** resummation
    - $\tilde{g}\tilde{g}$ ,  $\tilde{q}\tilde{g}$ ,  $\tilde{q}\tilde{q}^*$ ,  $\tilde{q}\tilde{q}$
- **LO EW** contributions, **LO one-loop** (Tree-level, loop induced, Higgs enhanced)
  - $\mathcal{O}(\alpha_s\alpha + \alpha^2 + \alpha_s^2\alpha^2 + \alpha_s^4)$
  - [Bozzi, Fuks, Klasen '05],
  - [Bornhauser, Drees, Dreiner, Kim '07 '09],
  - [Arhrib, Benbrik, Cheung, Yuan '09]
- $\mathcal{O}(\alpha_s^2\alpha)$ : NLO EW corrections
  - $\tilde{g}\tilde{g}$ ,  $\tilde{q}\tilde{g}$ ,  $\tilde{q}\tilde{q}^*$ ,  $\tilde{t}\tilde{t}^*$ ,  $\tilde{q}\tilde{q}$ ,  $\tilde{b}\tilde{b}^*$
  - [Hollik, Kollar, Trenkel '07],
  - [Beccaria et. al. '08],
  - [Hollik, Mirabella '08],
  - [Hollik, Mirabella, Trenkel '08],
  - [Mirabella '09],
  - [JG, Hollik, Mirabella, Trenkel '10],
  - [JG, Hollik, Mirabella] (in preparation)

# Squark & gluino production: EW production at tree-level

- $\mathcal{O}(\alpha^2)$ : pure EW tree-level contributions ( $\tilde{t}\tilde{t}^*$ ,  $\tilde{b}\tilde{b}^*$ ,  $\tilde{q}\tilde{q}^{(*)}$ ), e.g.



- $\mathcal{O}(\alpha_s\alpha)$ : EW-QCD tree-level interferences ( $\tilde{b}\tilde{b}^*$ ,  $\tilde{q}\tilde{q}^{(*)}$ ), e.g.



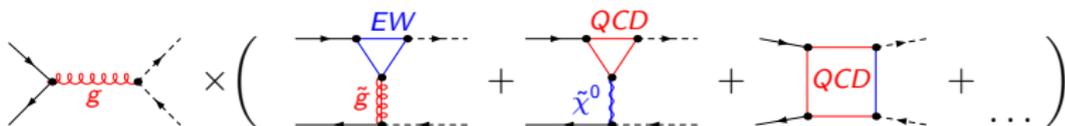
- $\mathcal{O}(\alpha_s\alpha)$ : photon induced processes ( $\tilde{t}\tilde{t}^*$ ,  $\tilde{b}\tilde{b}^*$ ,  $\tilde{q}\tilde{q}^*$ ,  $\tilde{g}\tilde{q}$ ), e.g.



# NLO EW: Contributions of $\mathcal{O}(\alpha_s^2\alpha)$

EW & QCD-like corrections have to be taken into account:

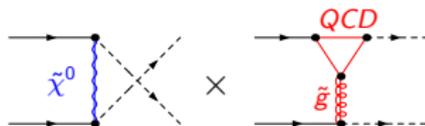
- QCD tree  $\times$  1-loop amplitude  $\mathcal{O}(\alpha_s\alpha)$ , e.g.



- EW tree  $\times$  1-loop amplitude  $\mathcal{O}(\alpha_s^2)$ , e.g.



only box diagrams lead to non-vanishing interferences



full QCD 1-loop amplitude

- Real photon, gluon and quark radiation.

# Singularities & divergences

- **UV divergences:** Renormalization required.

CTs have to be evaluated at  $\mathcal{O}(\alpha)$  and  $\mathcal{O}(\alpha_s)$ , respectively.

- **quarks, squarks, gluino** → **renormalized on-shell**  
Treat LH down-type squark as dependent quantity.
- **sbottom sector** → take  $m_{b_2}^{OS}$ ,  $m_b^{\overline{DR}}$ ,  $A_b^{\overline{DR}}$  as independent quantities.
- $\alpha_s$  →  **$\overline{MS}$  with five flavors** (same definition as in pdf)  
Caution with  $\hat{g}_s$ : needs symmetry restoring counterterm.

- **IR singularities:**

- Cancel after combining **virtual** and **real** corrections.

[Methods: **mass regularization** & **phase space slicing**;

gluonic corrections: **color correlations** in EW-QCD interferences.]

- **Collinear singularities:**

- Real photon and gluon **bremstrahlung**.
- **Factorization** and **redefinition** of the **PDFs** at  $\mathcal{O}(\alpha_s)$  and  $\mathcal{O}(\alpha)$ .

# Framework & Input parameters

- **Feynman diagrams** and **amplitudes** were generated and calculated within the **FeynArts**, **FormCalc**, **LoopTools** framework. [Hahn]
- Input: **SPS1a'** parameter set.
  - GUT-scale parameters evolved to 1TeV (softSUSY) [Allanach]
  - Compute **OS parameters**.

$$\begin{aligned} m(\tilde{u}_L) &= 560\text{GeV} & m(\tilde{d}_L) &= 566\text{GeV} & m(\tilde{g}) &= 609\text{GeV} \\ m(\tilde{u}_R) &= 543\text{GeV} & m(\tilde{d}_R) &= 539\text{GeV} & & \end{aligned}$$

- **Renormalization scale** for  $\alpha_s$ :  $\mathcal{O}(\text{mass of external particles})$
- **PDF** set: **MRST2004QED** [Martin, Roberts, Stirling, Thorne]
- **Fully flexible code** to compute **NLO EW** cross sections and distributions.

# Total hadronic X-section for 14 TeV LHC

**Born** and **EW** contributions to the **total cross section**:

SPS1a'	$\sigma^{LO}$ $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\Delta\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\Delta\sigma^{EW,LO}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	$\delta$
$\tilde{g}\tilde{g}$	6187 fb	-4 fb	-	-	0.07%
$\tilde{g}\tilde{q}$	20827 fb	-238 fb	10 fb	-	-1.1 %
$\tilde{t}\tilde{t}^*$	2856 fb	-54 fb	42 fb	2 fb	-0.4 %
$\tilde{q}\tilde{q}^*$	2251 fb	-12 fb	24 fb	-37 fb	-1.1%
$\tilde{q}\tilde{q}$	5444 fb	-147 fb	-	413 fb	4.9 %
$\tilde{b}\tilde{b}^*$ (preliminary)	728 fb	-9 fb	3 fb	1 fb	-0.6 %

$$\delta = (\Delta\sigma^{NLO} + \Delta\sigma^{\gamma g/\gamma q} + \Delta\sigma^{EW,LO})/\sigma^{LO}$$

# Total hadronic X-section, LL only, for 14 TeV LHC

**Born** and **EW** contributions to the **total cross section**:

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$\tilde{g} \tilde{q}_L$	10010 fb	-248 fb	5 fb	—	-2.4 %
$\tilde{t}_2 \tilde{t}_2^*$	186 fb	-32 fb	4 fb	0.3 fb	-14.8%
$\tilde{q}_L \tilde{q}_L^*$	1016 fb	-10 fb	11 fb	-22 fb	-2.0%
$\tilde{q}_L \tilde{q}_L$	1718 fb	-75 fb	—	379 fb	17.6%
$\tilde{b}_1 \tilde{b}_1^*$ (preliminary)	425 fb	-6 fb	2 fb	1 fb	-0.7%

$$\delta = (\Delta\sigma^{NLO} + \Delta\sigma^{\gamma g/\gamma q} + \Delta\sigma^{EW,LO})/\sigma^{LO}$$

# Total hadronic X-section, LL only, for 14 TeV LHC

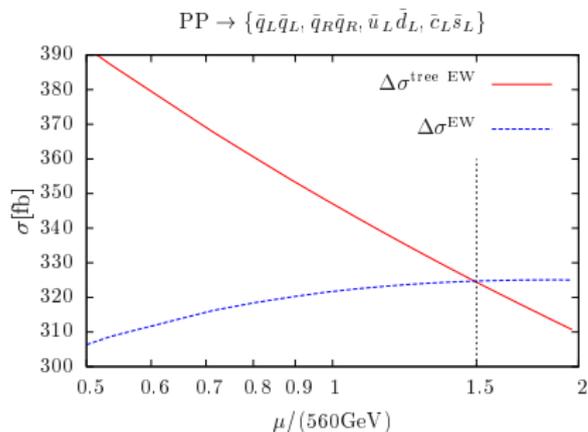
**Born** and **EW** contributions to the **total cross section**:

SPS1a'	$\sigma^{LO}$ $\mathcal{O}(\alpha_s^2)$	$\Delta\sigma^{NLO}$ $\mathcal{O}(\alpha_s^2\alpha)$	$\Delta\sigma^{\gamma g/\gamma q}$ $\mathcal{O}(\alpha_s\alpha)$	$\Delta\sigma^{EW,LO}$ $\mathcal{O}(\alpha^2+\alpha_s\alpha)$	$\delta$
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$\tilde{q}_L \tilde{q}_L$ : huge tree-level contribution gets compensated by NLO EW correction.

# Scale dependence

Scale dependence of **tree-level EW** and **NLO EW** cross section:  
(Consider only processes with non vanishing tree-level interference.)



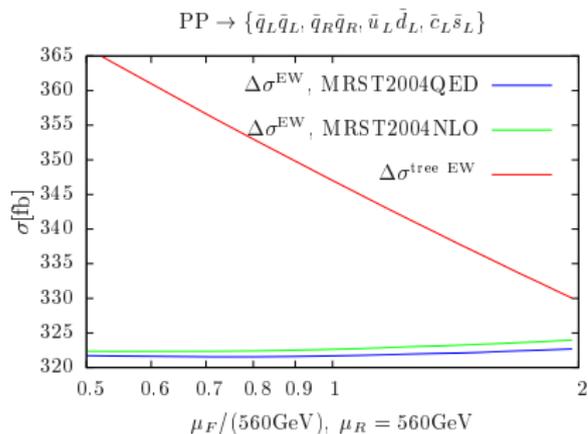
pdf set used:

- **MRST2001LO** for LO EW cross section.
- **MRST2004QED** for NLO EW cross section.

- Scale dependence **reduces** at NLO EW.
- LO EW cross section overestimated in case  $\mu = m_{\bar{q}}/2$  is taken.  
→ NLO EW computation needed to make reliable predictions.

# Scale dependence

$\mu_F$  dependence of tree-level EW and NLO EW cross section:  
(Consider only processes with non vanishing tree-level interference.)



pdf set used:

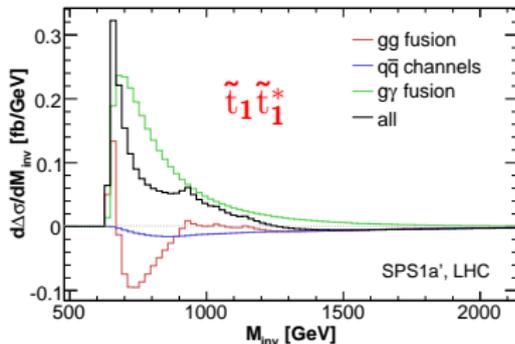
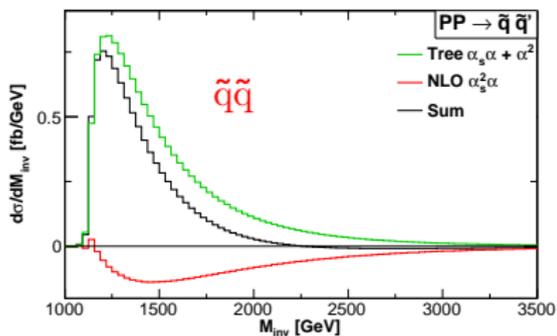
- MRST2001LO for LO EW.
- MRST2004QED for NLO EW.
- MRST2004NLO for NLO EW.  
(no QED factorization)

- Almost no  $\mu_F$  dependence left at NLO EW.
- Effects due to QED evolution in PDF's are small.

as expected from  
[Kripfganz, Perl '88]  
[Spiesberger '95]  
[Bauer, Keller, Wackerath '98]  
[Roth, Weinzierl '04]

# $M_{inv}$ distributions

## Electroweak contributions for $\tilde{q}\tilde{q}$ and $\tilde{t}_1\tilde{t}_1^*$



$\tilde{q}\tilde{q}$ : NLO EW distribution similar to tree-level EW.

$\tilde{t}_1\tilde{t}_1^*$ : Interplay of different channels:  $\gamma$  correction are of the same size.

# Summary & Conclusions

- If SUSY is realized at the TeV scale:  
**Squarks** and **gluinos** will be produced at a **very high rate** @LHC.
- Size of **EW NLO** corrections depends on **squark chirality**:
  - Only a **few percent** in the **inclusive case**.
  - Can be **> 10%** in the case of **left-handed** particle production.
- **Scale dependence** is strongly **reduced**.
  - **EW predictions** become more **reliable**.
- **EW contributions** to total cross section often are small.
  - Can become **important in distributions**.
- **NLO EW** contributions embedded in **fully flexible code**.
  - perform scan in parameter space, apply cuts, etc.

# Backup Slides

# Experimental Searches for Squarks and Gluinos

- **Squark & gluino** mass limits  
CDF, Tevatron Run II

$$m_{\tilde{g}} \geq 280 \text{ GeV}$$

$$m_{\tilde{q}} \geq 370 \text{ GeV}$$

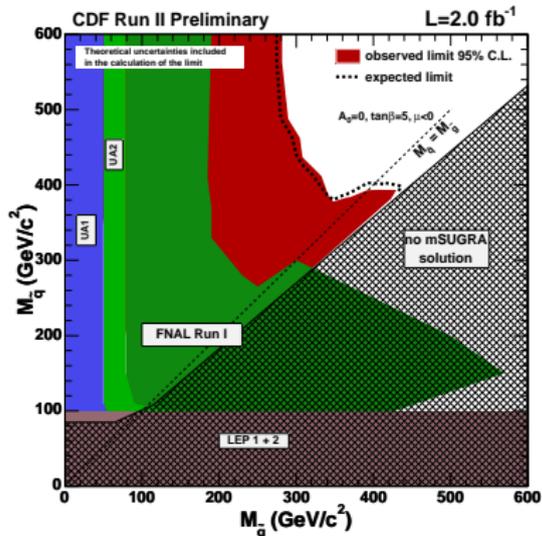
[CDF Note 9229]

- **Stop** mass limits  
CDF, Tevatron Run II

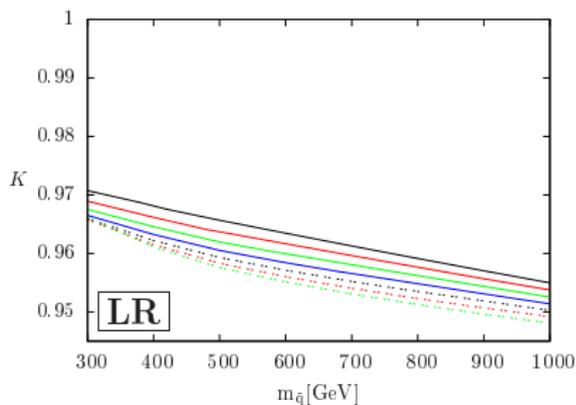
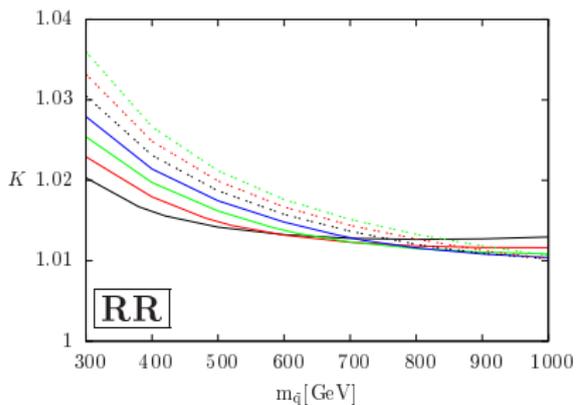
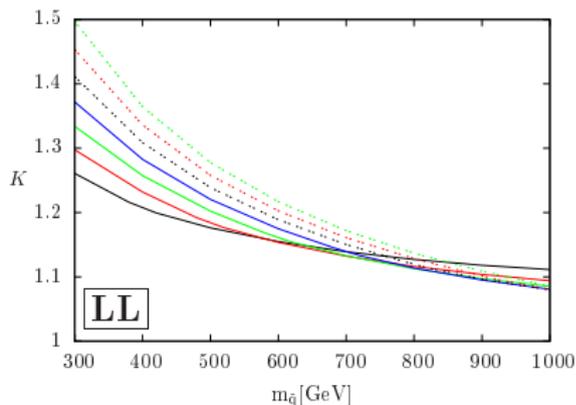
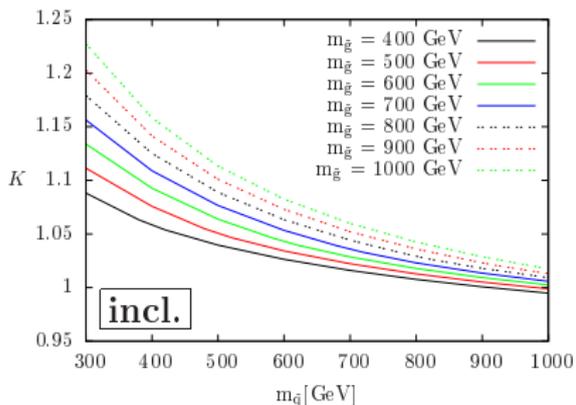
$$m_{\tilde{t}} \geq 132 \text{ GeV for } m_{\tilde{\chi}^0} = 132 \text{ GeV}$$

[0707.2567 hep-ex]

- Until now: agreement between experiment and SM predictions.
- Further analysis needs improved theoretical predictions.



# $\tilde{q}\tilde{q}$ production: $m(\tilde{q})$ and $m(\tilde{g})$ dependence



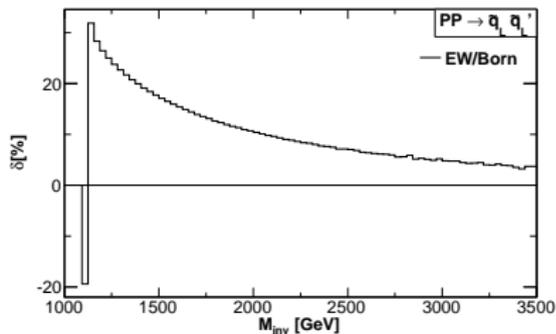
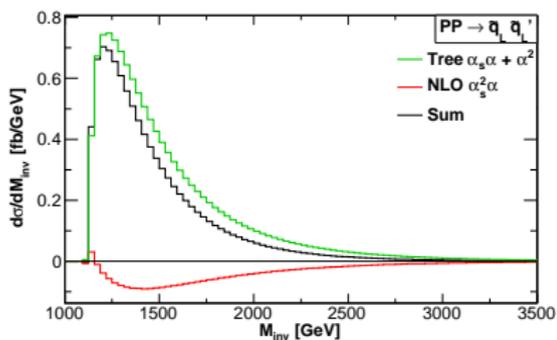
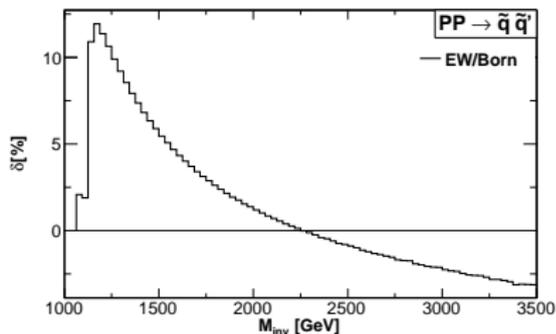
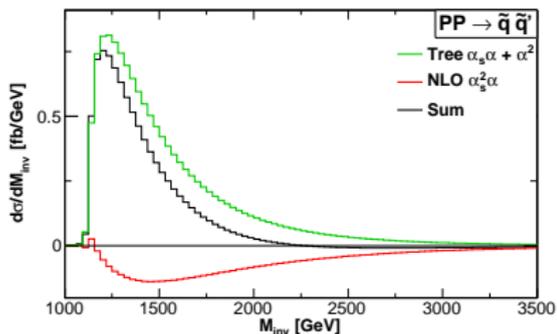
$$K = \sigma^{NLO} / \sigma^{LO}$$

[All other parameters are set to their SPS1a' values.]

# $M_{inv}$ distributions

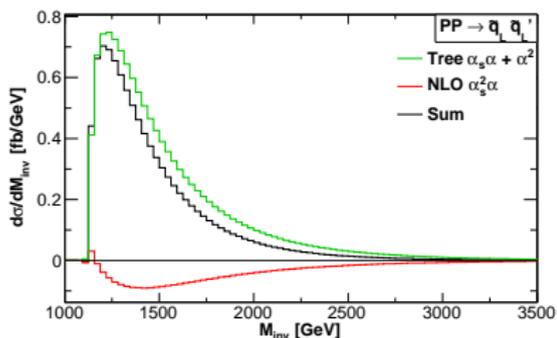
Electroweak contributions

$$\delta = \mathcal{O}(\alpha_s \alpha + \alpha^2 + \alpha_s^2 \alpha) / \mathcal{O}(\alpha_s^2)$$

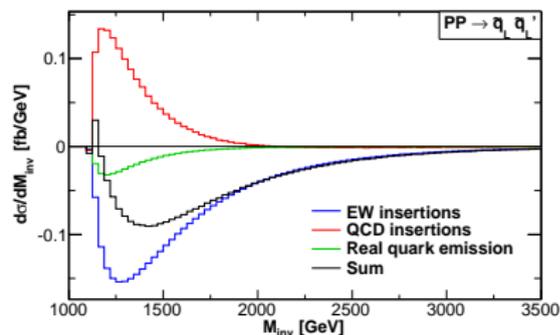


# $M_{\text{inv}}$ distribution

## Electroweak contributions

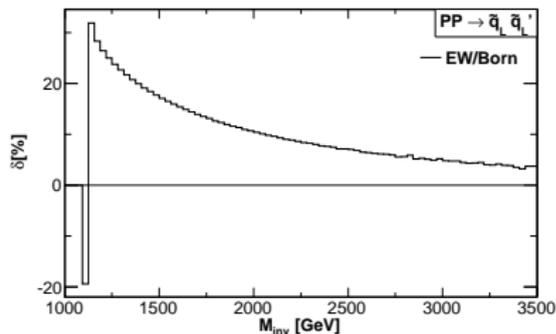


## $\mathcal{O}(\alpha_s^2 \alpha)$ : different channels



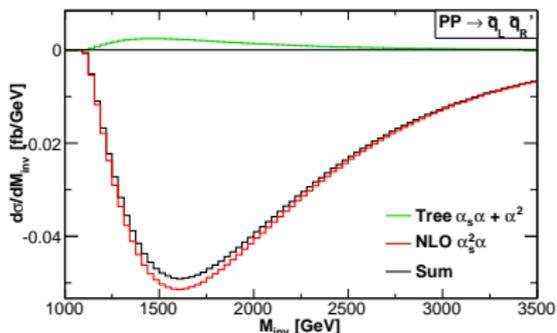
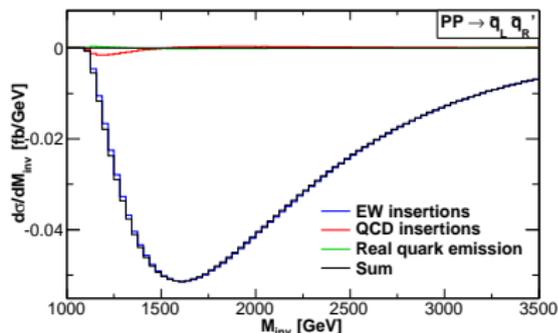
- Process:  $PP \rightarrow \tilde{q}_L \tilde{q}'_L$
- Contributions partially cancel!

$$\delta = \mathcal{O}(\alpha_s \alpha + \alpha^2 + \alpha_s^2 \alpha) / \mathcal{O}(\alpha_s^2)$$



# $M_{\text{inv}}$ distribution

Electroweak contributions

 $\mathcal{O}(\alpha_s^2 \alpha)$ : different channels

- Process:  $PP \rightarrow \tilde{q}_L \tilde{q}'_R$
- NLO EW contribution  
 $\gg$   
 tree-level EW contribution.

$$\delta = \mathcal{O}(\alpha_s \alpha + \alpha^2 + \alpha_s^2 \alpha) / \mathcal{O}(\alpha_s^2)$$

